

## ACTIVE FORCE GENERATION SYSTEM FOR MINIMIZING VIBRATION IN A ROTATING SYSTEM

### Technical Field

This invention relates to vibration isolators, and more particularly, to a new and useful isolation system for minimizing in-plane vibrations produced in a rotating system, 5 and still more particularly, to an isolation system that minimizes system weight, aerodynamic drag, and complexity while concomitantly providing active control and adjustment during operation for optimal efficacy across a wide spectrum of operating speeds.

### Background of the Invention

10 Vibration isolation or absorption is oftentimes desirable for nulling or canceling vibrations associated with a rotating system. Such vibrations, when left unattenuated or unabated, may lead to structural fatigue and premature failure of system components. Furthermore, inasmuch as such vibrations may be transmitted through adjacent support structure to, for example, an aircraft avionics bay or to areas occupied by passengers, 15 other components and cabin area remote from the source of the vibration, may be subject to these same potentially damaging or disturbing vibrations (albeit perhaps lower in amplitude due to energy absorption by the interconnecting structure). Consequently, it is most desirable to isolate or absorb these vibrations at or near the source of the vibration in the rotating system

20 One application which best exemplifies the need for and advantages derived from vibration isolation/absorption devices is the main torque driving hub of a helicopter rotor system. Typically, the main rotor of a helicopter, which comprises a central torque drive hub member for driving a plurality of lift producing rotor blades, is subject to a variety of aerodynamic and gyroscopic loads. For example, as each rotor blade advances or retreats 25 relative to the freestream airflow, it experiences a sharp rise and fall of in-plane

aerodynamic drag. Furthermore, as the tip of each rotor blade advances with each revolution of the rotor system, the relative velocity seen by the blade tip approaches supersonic Mach numbers. As such, large variations are caused to occur in the various coefficients which define blade performance (e.g., moment, lift and drag coefficients).

- 5      Moreover, gyroscopic and Coriolis forces are generated causing the blades to "lead" or "lag" depending upon cyclic control inputs made to the rotor system. All of the above generate substantial in-plane and out-of-plane vibrations which, if not suppressed, isolated or otherwise abated, are transmitted to the cockpit and cabin, typically through the mounting feet of the helicopter main rotor gearbox.
- 10     Various vibration isolation systems have been devised to counteract/oppose and minimize these in-plane and out-of-plane vibrations. Mast-mounted vibration isolators suppress or isolate in-plane vibrations at a location proximal to the source of such in-plane vibrations whereas transmission, cabin or cockpit absorbers dampen or absorb out-of-plane vibrations at a location remotely disposed from the source. Inasmuch as the
- 15     present invention relates to the isolation of in-plane vibrations, only devices designed to counteract/oppose such vibrations will be discussed herein.

Vincent et al. U.S. Pat. Nos. 4,145,936 and 4,225,287 disclose mast-mounted vibration isolators having a plurality of resilient arms (i.e., springs) extending in a spaced-apart spiral pattern between a hub attachment fitting and a ring-shaped inertial mass.

- 20     Several pairs of spiral springs (i.e., four upper and four lower springs) are mounted to and equiangularly arranged with respect to both the hub attachment fitting and the inertial mass so as to produce substantially symmetric spring stiffness in an in-plane direction. The spring-mass system, i.e., spiral springs in combination with the ring-shaped mass, is tuned in the non-rotating system to a frequency equal to  $N * \text{rotor RPM}$  (e.g., 4P for a
- 25     four-bladed rotor) at normal operating speed, so that in the rotating system it will respond to both  $N+1$  and  $N-1$  frequency vibrations (i.e., 3P and 5P for a four-bladed rotor). N is the number of rotor blades.

While the spiral spring arrangement of the '936 and '287 patents produce a relatively small width dimension (i.e., the spiraling of the springs increases the effective

spring rate), the height dimension of each vibration isolator is increased to react out-of-plane loads via the upper and lower pairs of spiral springs. This increased profile dimension increases the profile area, and consequently the profile drag produced by the isolator. Furthermore, the spiral springs must be manufactured to precise tolerances to obtain the relatively exact spring rates necessary for efficient operation. As such, manufacturing costs are increased. Furthermore, these vibration isolators are passive devices which are tuned to a predetermined in-plane frequency. That is, the vibration isolators cannot be adjusted in-flight or during operation to isolate in-plane loads which may vary in frequency depending upon the specific operating regime.

U.S. Patent 3,540,809, 4,057,363 & 4,083,654 issued to inventors Kenigsberg and Paul, et al., disclose yet another general configuration of isolator known as a "bifilar". These mast-mounted vibration isolators comprise a hub attachment fitting connected to and driven by the helicopter rotorshaft, a plurality of radial arms projecting outwardly from the fitting and a mass coupled to the end of each arm via a rolling pin arrangement. That is, a pin rolls within a cycloidally shaped bushing thereby permitting edgewise motion of each mass relative to its respective arm. The geometry of the pin arrangement in combination with the centrifugal forces acting on the mass (imposed by rotation of the bifilar) results in an edgewise anti-vibration force at a 4 per revolution frequency which is out-of-phase with the large 4 per revolution (or "4P" as it is commonly referred to as helicopter art) in-plane vibrations of the rotor hub for a 4 bladed helicopter. The frequency of 4P is the frequency as observed in a nonrotating reference system.

More specifically, pairs of opposed masses act in unison to produce forces which counteract forces active on the rotor hub. In Fig.1, a schematic of a pair of bifilar masses, at one instant in time, are depicted to illustrate the physics of the device. Therein, the masses MI, MII are disposed at their extreme edgewise position within each of the respective cycloidal bushings BI, BII. The masses MI, MII produce maximum force vectors F/2, which produce a resultant vector F at the center, and coincident with the rotational axis, of the rotating system. Furthermore, the combined or resultant force vector F is equal and opposite to the maximum vibratory load vector P active on the rotor

at the same instant of time. This condition, when the bifilar produces and equal and opposite force  $F$  that opposes the rotor load  $P$ , reflects ideal operation of the bifilar. Excessive bifilar damping or manufacturing imperfections will cause the bifilar output force  $F$  to differ from the disturbing force  $P$  produced by the rotor either in magnitude or 5 phase best suited to nullify the rotor loads. This condition will cause unwanted fuselage vibration. It will also be appreciated that for the masses to produce the necessary shear forces to react the in-plane vibratory loads of the rotor system, counteracting bending moments are also produced. These force couples impose large edgewise bending loads in 10 the radial arms, and, consequently, the geometry thereof must produce the necessary stiffness ( $EI$ ) at the root end of the arms. As such, these increased stiffness requirements require larger, heavier bifilar arms.

While the bifilar system has proven effective and reliable, the weight of the system, nearly 210 lbs, is detrimental to the overall lifting capacity of the helicopter. For example, the weight of the bifilar system displaces a passenger and/or increases fuel 15 consumption. To appreciate the significance of the increased weight, it has been estimated that for each pound of additional weight, direct operating cost of the helicopter increases by approximately \$10,000. Furthermore, the pin mount for coupling each mass to its respective radial arm routinely and regularly wear, thus requiring frequent removal and replacement of the cyclical bushings. This increases the Direct Maintenance Costs 20 (DMC) for operating the helicopter, which contributes, to the fiscal burdens of the bifilar system and the helicopter.

Therefore, a need exists for an isolation system to reduce vibrations in a rotating system that isolates a wide spectrum of vibratory loads; especially large amplitude loads, minimizes system weight, reduces aerodynamic drag and reduces DMC.

### **Disclosure of the Invention**

It is the object of the present invention to provide a vibration isolation system which is controllable for varying the range of isolation frequencies.

It is another object of the present invention to provide such a vibration isolation system which absorbs large amplitude vibrations while minimizing system weight.

It is another object of the present invention to provide such a vibration isolation system which employs simple, easily manufactured components for reducing fabrication costs.

It is another object of the present invention to provide such a vibration isolation system which is insensitive to damping and manufacturing imperfections.

### **Brief Description of the Drawings**

A more complete understanding of the present invention and the attendant features and advantages thereof may be had by reference to the following detailed description when considered in conjunction with the accompanying drawings wherein:

Fig. 1 is a schematic of a prior art bifilar isolation device for illustrating certain physical characteristics thereof.

Fig. 2 is a side sectional view of a helicopter main rotor, including a main rotor shaft having an isolation system according to the present invention mounted to the upper mast or shaft extension member of the rotor.

Figs. 3a - 3c depict schematic views of various operating conditions of the inventive isolation system.

Fig. 4 is a side sectional view of one embodiment of the isolation device.

### **25 Best Modes for Carrying Out the Invention**

The isolation system of the present invention is described in the context of a helicopter rotor system, such as that employed in an Army BLACK HAWK helicopter produced by Sikorsky Aircraft Corporation. One skilled in the art, however, will

appreciate that the present invention has utility in any rotating system which produces vibratory loads (noise). The invention is especially useful in rotating systems that produce large vibratory loads that vary depending upon different operating regimes or variable operating speeds.

5 Referring to Fig. 2, the vibration isolator 10 according to the present invention is disposed in combination with a rotor system 2 comprising a main rotor shaft 4 (rotating member) that is driven about its rotational axis 6 by a torque driving transmission 8. In the described embodiment, the rotor system 2 also comprises a propeller-type hub 12 having four radial arms that mount to and drive each rotor blade 16. The vibration isolation system 10 is mounted to a flanged end 13 of the main rotor shaft 4 by means of a hub attachment fitting 18. Vibratory forces active on the rotor system 2 are generated by a variety of factors, although the dominant vibrations originate from aerodynamic and/or gyroscopic forces generated by each rotor blade 16. A four bladed rotor system produces 3P vibratory loads, i.e., in a single revolution, the magnitude of the load vector varies from a minimum to a maximum value three times in the rotating frame of reference. This resolves into 4P vibration in the nonrotating frame of reference due to the addition of the 1P rotor rotational speed. While a variety of factors influence the vibratory spectrum of a rotor system, such 4P vibrations are generally a result of each rotor blade experiencing maximum lift when advancing and minimum lift when retreating.

10 15 20 25 Referring to Figs. 2 and 4, the vibration isolator 10 comprises: two, essentially coplanar, masses M1, M2, a means 30 for driving the masses M1, M2 about the rotational axis 6 of the main rotor shaft 4, a means 40 for issuing control signals to the drive means 30 to control the rotational speed and relative angular position of the masses M1, M2 and a power source 50 for energizing the drive means 30 and controller-amplifier 40. The masses M1, M2 are (i) disposed at a predetermined distance R from the main rotor shaft axis 6, (ii) driven in the same or opposing rotational direction as the main rotor shaft axis 6 and (iii) driven at a rotational speed at least 3P greater than the rotational speed 1P of the rotor shaft 4. In the preferred embodiment, the drive means 30 preferably comprises a pair of electric motors 34a, 34b for driving each of the masses M1, M2 by means of a

relatively small diameter, constant cross-section radial arm 36 (shown schematically in Fig. 3a - 3c). Moreover, the electric motors 34a, 34b are independent of each other, e.g., may be driven at different rotational speeds to enable variation of the isolation force magnitude and phase.

5 As shown in Fig. 4, the control means 40 requires a speed sensor 42 for issuing signals 42s indicative of the rotational speed 1P of the rotor shaft 4, and a signal processing and amplifier means 44, responsive to the speed signals 42s, for issuing control signals 44s to the drive means 30 indicative of the rotational velocity and relative angular position of each of the masses M1, M2. While the speed sensor 42 may be a  
10 dedicated unit for sensing rotor speed, the same information may be obtained from a transmission alternator or generator 50 which turns at a predefined speed relative to the rotor speed. The alternator or generator 50 supplies power to the controller-amplifier 44 through the slipring 54. Hence, the controller 40 may use voltage phase information from such devices to issue the appropriate control signals to the drive means 30.

15 While the isolation system 10 may employ a simple controller-amplifier 40 having a predefined schedule or model of the vibrations, e.g., at prescribed rotor speeds, the preferred embodiment also employs a vibration sensing device or system. As such, the control means 40 further comprises one or more vibration feedback sensors 51 for issuing vibration signals 51s indicative of the vibrations (e.g., amplitude, frequency and phase) of  
20 the helicopter rotor hub 12. The control means 40, therefore, samples vibration levels at predefined intervals or rates to identify a trend - positive (lower vibration levels) or negative (larger vibration levels). Accordingly, as vibration levels change, the controller 40 issues modified signals 44s to the drive means 30 until an optimum combination of rotational speed, force magnitude and phase are achieved.

25 The isolation system 10 may be powered by any of a variety of known methods, especially methods which may require transmission from a stationary to a rotating reference system. In the described embodiment shown in Fig. 4 the drive and control means, 30 and 40, respectively, are powered by a 15 kVa generator 50 which provides a 115 volt potential at 400 Hz and with 3 phases (standard AC power for helicopters).

Power is transferred from the stationary system to the rotating system via a conventional cylindrical slip ring 54. Only a small amount of additional weight is required inasmuch as the slip ring 54 is pre-existing and used for powering other systems e.g., rotor blade de-icing system. This slip ring may also be used to communicate the control signals 42s to the 5 drive means 30 when the controller 40 is mounted in the fuselage rather than on the rotor system 2.

In operation, the masses M1, M2 (shown in Figures 3a-3c) are driven by the drive means 30 at a rotational speed greater than the rotational speed of the rotating system and 10 appropriately positioned to yield a load vector P10 which is equal and opposite to the load vector P2 produced by the rotor system 2. This counteracting load vector P10 can be viewed as a vector which attempts to cancel or null the displacement of the rotor shaft 4. In the described embodiment, the masses turn at a rotational speed. Inasmuch as the drive means 30 is mounted directly to the rotating shaft 4 of the rotor system 2, the drive means 30 need only drive the masses M1, M2 three additional revolution per cycle (for each 15 revolution of the rotor system) to achieve the desired 4P frequency. That is, since the masses M1, M2 are, in a rotating reference system, driven at one revolution per cycle by the rotor system 2 itself, the drive means 30 need only augment the rotational speed by the difference (4P – 1P) to achieve the necessary 4P in the stationary reference system.

Figs. 3a – 3c depict various operating positions of the masses M1, M2 to 20 emphasize the function and versatility of the isolation system 19. In Fig. 3a, the masses M1, M2 are essentially coincident and act in unison to produce a maximum force vector P10<sub>MAX</sub>. In Fig. 3b, the masses M1, M2 define a right angle (90 degrees) therebetween thereby producing a force vector P10<sub>MAX/</sub> (sqrt (2)) that is a fraction of the magnitude of the maximum force vector. In Fig. 3c, the masses M1, M2 define a straight angle (180 25 degrees) and are essentially opposing to cancel the vectors produced by each of the masses M1, M2 independently or individually. In Figure 4 the controller 40 issues signals to the drive means 30 to (a) drive the masses M1, M2 at a rotational speed greater than that of the rotating system and (b) produce a counteracting load of the correct magnitude and phase to efficiently isolate vibrations.

The ability to independently vary the relative angular position of the masses M1, M2 is especially valuable in applications wherein the magnitude of the vibratory load active in/on the rotating system varies as a function of operating regime or operating speed. In a rotorcraft, for example, it is common to require the highest levels of vibration isolation in high speed forward flight i.e., where the rotor blades are experiencing the largest differential in aerodynamic loading from advancing to retreating sides of the rotor system. Consequently, it may be expected that the drive means 30 produce the maximum load vector  $P_{10\text{MAX}}$  such as illustrated in Fig. 3a. In yet another example, it is anticipated that the lowest levels of vibration isolation would occur in a loiter or hovering operating mode, where the rotor blades are exposed to the same aerodynamic and gyroscopic affects. Consequently, it may be expected that the drive means 30 produce no or a minimum load vector  $P_{10\text{MIN}}$  such as illustrated in Fig. 3c.

Thus far, the discussion herein has concentrated on the rotational speed and angular position of the masses M1, M2 to produce vibration isolation. While this feature of the invention is a primary aspect of the invention, the configuration of the inventive isolation system 10 produces counteracting load vectors  $P_{10}$  which act though the rotational axis of the rotor shaft 4. That is, the line of action of the load vector  $P_{10}$ , whether the masses M1, M2 are coincident or opposing, intersects the rotational axis and produces pure radial loads. As such, the radial arms of the isolation system 10 are principally loaded in tension rather than a combination of tensile and bending moment loads (as seen in the prior art). A consequence of this loading condition is a reduction in system weight inasmuch as the radial arms 36 need not produce high edgewise strength to react bending moment loads.

Furthermore, tensile loading in the radial arms 36 enables the use of a constant-cross-section structure to react the centrifugal loads produced by each of the masses M1, M2. Moreover, directional strength materials (non-isotropic) may be employed such as unidirectional fiber reinforced composites. As a result, the isolation device may be produced using low cost manufacturing techniques and materials. For example, cylindrical raw material stock, cut to the proper length, may be purchased and employed

without secondary processing. Also, the use of unidirectional composites enables yet further weight reduction

Although the invention has been shown and described herein with respect to a certain detailed embodiment of a mast-mounted helicopter isolator, it will be understood 5 by those skilled in the art that a variety of modifications and variations are possible in light of the above teachings. It is therefore to be understood that, within the scope of the appended claims, the present invention may be practiced otherwise than as specifically described hereinabove.